Early Response of Soil Organic Fractions to Tillage and Integrated Crop–Livestock Production

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Tillage, cropping system, and cover cropping are important management variables that control the quantity, quality, and placement of organic matter inputs to soil. How soil organic matter and its different fractions respond to management has not been comprehensively studied in integrated crop–livestock systems. We conducted a 3-yr field experiment on a Typic Kanhapludult in Georgia in which long-term pasture was terminated and converted to annual crops. Tillage systems were conventional (CT, moldboard plowed initially and disked thereafter) and no-till (NT). Cropping systems were summer grain with winter cover crop and winter grain with summer cover crop. Cover crops were either grazed by cattle or left unharvested. Total organic C was highly stratified with depth under NT and relatively uniformly distributed with depth under CT. All soil C and N fractions were greater under NT than under CT at a depth of 0 to 6 cm. Tillage system had the most dominant influence on all soil C and N fractions, and cropping system the least. At the end of 3 yr, total organic C at a depth of 0 to 30 cm was lower under CT than under NT (42.6 vs. 47.4 Mg ha^{-1} [$P < 0.001$]). Potential C mineralization was also lower under CT than under NT (1240 vs. 1371 kg ha^{-1} during 24 d [$P = 0.02$]). At a depth of 0 to 30 cm, cover crop management had no effect on soil C and N fractions, but within the surface 6 cm some changes occurred with grazing of cover crops by cattle, the most dramatic of which were 1 ± 9% increase in soil microbial biomass C and 3 ± 16% decrease in potential C mineralization. To preserve high surface-soil C and N fractions and total plow-layer contents, NT cropping following termination of perennial pasture is recommended. In addition, since cattle grazing cover crops did not consistently negatively influence soil C and N fractions, integrated crop–livestock systems are recommended as a viable conservation approach while intensifying agricultural land use.

Abbreviations: CT, conventional tillage; NT, no-till.

SOIL BIOLOGY & BIOCHEMISTRY

Soil organic matter is a critical component in maintaining soil quality (Follett et al., 1987). Pastures are known to improve soil organic C and N (Franzluebbers et al., 2000c), which leads to retention of organically bound nutrients, improved water relations, and better overall soil functioning (Weil and Magdoff, 2004). Tillage and crop management under conditions of initially high soil organic matter content following termination of pasture have not been thoroughly evaluated, since most cropping occurs on soils stripped of organic matter from previous degradative tillage practices (Langdale et al., 1992). No-till management of crops following termination of pastures could be a viable approach to preserve accumulated soil organic matter, rather than a traditional approach of moldboard plowing of pasture. Few data are available, however, to quantify the expected difference in decline of soil organic matter between conventional and conservation tillage systems following pasture (Hargrove et al., 1982).

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Climatic conditions in the southeastern United States are characterized by high precipitation to potential evapotranspiration ratios (P/PET) during the winter growing season (1.96, October–March) and low to moderate P/PET during the summer growing season (0.75, April–September). Cover crops can be successfully grown throughout the year and they could help mitigate potential NO_3 leaching (Tonitto et al., 2006). The impact on surface soil conditions of whether and when cattle are to graze a cover crop (i.e., cool season vs. warm season) has received little attention. Cattle traffic on a cover crop during extended wet conditions could negatively alter soil structural conditions, temperature and water relations, soil biological activity, and nutrient dynamics.

About 12% of the land area in the southern Piedmont of the United States is devoted to pasture production, mostly for grazing by cattle (National Agricultural Statistics Service, 2004). Previous research has shown that grazing of warm-season grasses in the summer can have positive impacts on soil organic C and N accumulation and no observable detriment to surface soil compaction (Franzluebbers et al., 2001). Rotation of pastures with crops often provides soil quality, yield, and soil erosion benefits (Studdert et al., 1997; Garcia-Prechac et al., 2004). The role of ungulates in pasture–crop rotations, however, does not have to be limited to the medium- or long-term pasture phase alone. Cover crops following grain crops can be an excellent source of high-quality forage to be utilized in small, mixed-use farming operations (Franzluebbers and Stuedemann, 2007), such as those commonly found throughout the southeastern United States. A potential impact of large herbivores grazing cover crops, however, could be compaction due to hoof action, as observed in conventionally tilled southern Piedmont soils under relatively low soil organic matter conditions (Tollner et al., 1990). Surface residue cover may provide a significant buffer against ungulate trampling effects, such that NT crop production following long-term pasture may mitigate negative trampling effects.

Particulate organic matter is considered an intermediately decomposable fraction of organic matter, representing in many ways the slow pool of the continuum active–slow–passive soil organic matter (Parton et al., 1987; Cambardella and Elliott, 1992). Therefore, particulate organic C and N could be sensitive indicators of changes in soil organic matter brought about by changes in management. Particulate organic C often increases with a reduction in tillage intensity (Cambardella and Elliott, 1992; Wander et al., 1998) and can be the major fraction of total organic C near the soil surface under pastures (Franzluebbers and Stuedemann, 2002a).

Biologically active C and N fractions, including microbial biomass and mineralizable C and N, are important for understanding nutrient dynamics, which can affect short-term nutrient immobilization during rapid microbial growth and activity, as well as long-term storage and subsequent slow release of nutrients. Detailed information on the near-surface vertical distribution of these soil C and N fractions under integrated crop–livestock systems is lacking. Knowledge of the quantitative and qualitative changes in biologically active soil C and N fractions in response to tillage is generally known (Doran, 1980, 1987), but how these fractions respond to cover crop management, including grazing cattle has been scantly investigated.

Changes in where soil C and N are located within the soil matrix and how these affect soil structural stability can have impacts on how water infiltrates and is stored in soil, how and when nutrients are mineralized, and the development of soil biological diversity and potential activity (Carter, 2004). Not only is the vertical distribution of soil C and N fractions of importance, but their location within water-stable aggregates may also be of key significance to better understand C and N turnover in soil and its potential stabilization for long-term sustainability of the soil.

Our objectives were to characterize (i) the depth distribution of soil C and N fractions, (ii) the impacts of tillage and crop management on changes in soil C and N fractions during an initial 3-yr period of evaluation, (iii) the distribution of soil organic C and N in water-stable aggregates, and (iv) the temporal dynamics of stocks of C and N fractions within the upper 20 cm of soil. Our first hypothesis was that stratification of soil organic C and N fractions with depth would be maintained with conversion of pasture to cropping with NT, but a uniform distribution with depth would occur with CT. With time, the stratification of soil C and N fractions would decline even with NT. Our second hypothesis was that biologically active fractions of C and N would be more sensitive to management changes than total C and N. Our third hypothesis was that preservation of soil C and N fractions with NT would occur preferentially in macroaggregates rather than in microaggregates. Our fourth hypothesis was that the total contents of soil C and N fractions would decline most rapidly with CT, intermediately with NT, and remain stable with continuation of pasture. Our fifth hypothesis was that grazing of a winter cover crop would cause a decline in soil C and N fractions compared with an ungrazed winter cover crop or grazed summer cover crop due to trampling of a wet soil surface and enhanced organic matter decomposition.

MATERIALS AND METHODS

Site Characteristics and Management

The experiment was located near Watkinsville, GA (33°62′ N, 83°25′ W) on Cecil sandy loam and sandy clay loam soils (fine, kaolinitic, thermic Typic Kanhapludults) with 2 to 6% slope. The soil was moderately acidic (pH ~6) and contained moderate total N (1.2 g kg^{-1}) in the upper 20 cm. Mean annual temperature is 16.5°C, precipitation is 1250 mm, and pan evaporation is 1560 mm.

Since 1982, a total of 18 paddocks (0.7 ha each) were managed as tall fescue [*Lolium arundinaceum* (Schreb.) Darbysh.] pastures, varying in tall fescue–endophyte association and fertilization level (Belesky et al., 1988). Pastures were grazed with Angus cattle each year, primarily in spring and autumn. All fertilization was suspended after 1997 to help avoid further accumulation of inorganic N in the soil profile below 0.3 m (Franzluebbers et al., 2000b). In May 2002, 16 of the 18 pastures were terminated either with moldboard plow or glyphosate [*N*-(phosphonomethyl)glycine]. In May 2002, a new experimental design was imposed onto this previous design by randomly allocating four primary treatments in a stratified but randomized manner to account for previous management.

The experimental design from 2002 to 2005 consisted of a factorial arrangement of (i) tillage (conventional and no-till) and (ii) cropping system (summer grain with winter cover crop and winter grain with summer cover crop) with four replicated paddocks each, for a total of 16 main plots. Two of the original 18 pastures remained as control pastures. Main plots were split into grazed (0.5 ha) and ungrazed (0.2 ha) cover crop treatments.

Tillage systems were: (i) conventional disk tillage (CT) following harvest of each grain and cover crop and (2) NT with glyphosate to control weeds before planting. Tillage treatments were initiated in May 2002. Initial CT treatment consisted of moldboard plowing to a depth of 25 to 30 cm. Disk plowing only to a depth of 15 to 20 cm occurred in subsequent years. Pasture was terminated in the NT treatment with two applications of glyphosate (5.8 L ha^{-1} in May and 2.3 L ha^{-1} in June 2002).

Cropping systems were: (i) summer grain cropping (grain sorghum [*Sorghum bicolor* (L.) Moench] or corn (*Zea mays* L.), April–June planting and September–October harvest) with winter cover cropping [cereal rye (*Secale cereale* L.), November planting and May termination] and (ii) winter grain cropping [wheat (*Triticum aestivum* L.), November planting and May–June harvest] with summer cover cropping (pearl millet [*Pennisetum glaucum* (L.) R. Br.], June–July planting and September–October termination).

Cover crop management was: (i) no grazing and (ii) grazing with cattle to consume ~90% of available forage produced. Cover crops were stocked with yearling Angus steers in the summer of 2002 and in the spring of 2003. Thereafter, cow/calf pairs were used to simulate a more typical regional management approach. Ungrazed cover crops were grown until ~2 wk before planting of the next crop and either (i) mowed before CT operations or (ii) mechanically rolled to the ground in the NT system.

Application of N was relatively low during the first 3 yr (96 ± 7 kg N ha^{-1} yr^{-1}) but was adequate to assure early plant growth and development, with further growth dependent on the mineralization of stored nutrients in the soil organic matter. Extractable P and K concentrations in the surface 7.5 cm of soil were ≥100 mg P kg^{-1} soil and 400 mg K kg^{-1} soil, levels considered adequate for crop production. Plant and animal production were reported in Franzluebbers and Stuedemann (2007).

Soil Sampling and Analyses

Soil was collected in May 2002 (initiation) and in November to December of 2002 (end of 1 yr), 2003 (end of 2 yr), and 2004 (end of 3 yr). Soil was sampled at depths of 0 to 3, 3 to 6, 6 to 12, and 12 to 20 cm in May 2002 and additionally at 20- to 30-cm depth thereafter. A composite sample of eight cores in grazed plots and five cores in ungrazed plots was collected with a 4-cm-diameter probe. At each of the soil sampling locations, surface residue was collected from a 0.04-m^2 area before soil coring. Surface residue was dried (55°C, ≥3 d), ground to <1 mm, and a subsample analyzed for total C and N with dry combustion. Soil was dried at 55°C for ≥3 d and bulk density was calculated from the total dry weight of the soil and the volume of the coring device. For all subsequent laboratory analyses, soil was passed through a sieve with openings of 4.75 mm to remove gravel.

Total organic C and total N were determined with dry combustion on subsamples ground in a ball mill for 5 min. Soil pH was <6.5 and, therefore, total C was considered equivalent to organic C.

Particulate organic matter was isolated from soil by shaking 22.5- to 65-g subsamples of soil (inversely related to soil organic C concentration) in 100 mL of 0.01 mol L^{-1} $Na_4P_2O_7$ for 16 h, passing the mixture over a sieve with 0.053-mm openings, and collecting the contents remaining on the top of the sieve (Cambardella and Elliott, 1992; Franzluebbers et al., 1999). Samples were dried at 55°C for 24 h past visual dryness, weighed, ground to a fine powder in a ball mill, and analyzed for C and N concentration with dry combustion. Clay concentration from soil collected in November to December 2002 was determined before particulate organic matter determination in a 1-L cylinder with a hydrometer at the end of a 5-h settling period (Gee and Bauder, 1986).

Potential C mineralization was determined by placing two 22.5- to 65-g subsamples of soil in 60-mL glass jars, wetting to 50% water-filled pore space, and placing them in a 1-L canning jar along with 10 mL of 1 mol L^{-1} NaOH to trap CO_2 and a vial of water to maintain humidity (Franzluebbers et al., 1999). Samples were incubated at 25 ± 1°C for 24 d. Alkali traps were replaced at 3 and 10 d of incubation and CO_2–C determined by titration with 1 mol L^{-1} HCl in the presence of excess $BaCl_2$ to a phenolphthalein endpoint. At 10 d, one of the subsamples was removed from the incubation jar, fumigated with $CHCl_3$ under vacuum, vapors removed at 24 h, placed into a separate canning jar along with vials of alkali and water, and incubated at 25°C for 10 d. Soil microbial biomass C was calculated as the quantity of CO_2–C evolved following fumigation divided by an efficiency factor of 0.41 (Voroney and Paul, 1984; Franzluebbers et al., 1999). Potential C mineralization was the CO_2–C respired during 24 d, while the flush of CO_2–C following rewetting was considered from the first 3 d only. Potential N mineralization was determined from the difference in inorganic N concentration between 0 and 24 d of incubation. Inorganic N (NH_4–N + NO_2–N + NO_3–N) was determined from the filtered extract of a 10-g subsample of dried (55°C for 48 h) and sieved (<2 mm) soil that was shaken with 20 mL of 2 mol L^{-1} KCl for 30 min using salicylate–nitroprusside and Cd-reduction autoanalyzer techniques (Bundy and Meisinger, 1994).

Water-stable aggregate fractions were separated from a 50-g (0–3- and 3–6-cm depths) or 100-g (6–12-, 12–20-, and 20–30-cm depths) subsample of soil placed on a nest of sieves (17.5-cm diam. with openings of 1.0 and 0.25 mm), which were immersed directly in water and oscillated for 10 min (20-mm stroke length, 31 cycles min^{-1}). After removing the two sieves and placing them in an oven to dry, water containing soil passing the 0.25-mm sieve was poured over a 0.053-mm sieve, the soil was washed with a gentle stream of water, and the soil retained was transferred into a drying bottle with a small stream of water. All fractions were oven dried at 55°C for 3 d. Large macroaggregates were defined as the fraction 1.0 to 4.75 mm. Small macroaggregates were defined as the fraction 0.25 to 1.0 mm. Microaggregates were defined as the fraction 0.053 to 0.25 mm. Following drying and weighing of fractions, large macroaggregates were ball-milled for 5 min to obtain greater uniformity. All three aggregate fractions were analyzed for total C and N with dry combustion.

Statistical Analyses

The experimental design was considered a multiple split-block design with four replications. Main plots were a factorial arrangement of tillage (n = 2) and cropping system (n = 2). Cover crop management (n = 2) was a split plot in horizontal space. Depth of sampling (n = 4 in May 2002 and n = 5 in November–December 2002, 2003, and 2004) was a split plot in vertical space. Year of sampling (n = 4) was a split plot in time. Soil organic C and N fractions within a depth increment and year of sampling were analyzed for variance due to tillage, cropping system, and cover crop management using SAS (SAS Institute, Cary, NC). Error terms were replication × tillage × cropping system for main-plot effects and replication × tillage × cropping system × cover crop management for split-plot effects. Temporal change in soil properties was evaluated with linear regression. Stratification ratio of soil properties was calculated from the weighted concentration at a depth of 0 to 6 cm divided by the concentration at a depth of 12 to 20 cm (Franzluebbers, 2002a). Differences among treatments were considered significant at $P \leq 0.05$, but significance of difference is also noted here at levels of $P \leq 0.01$ and $P \leq 0.001$.

RESULTS AND DISCUSSION

Soil Physical Conditions

At the end of Year 1, the clay and sand concentration of the soil was significantly affected by tillage management (Fig. 1). Moldboard plowing brought up soil with a higher clay con-

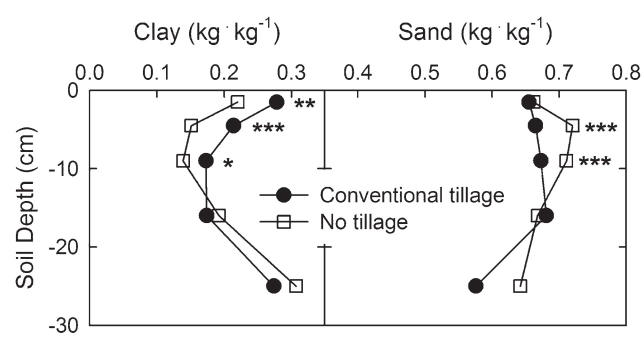

Fig. 1. Clay and sand concentration at the end of 1 yr as affected by tillage management. * Significant at $P \leq 0.05$. ** Significant at $P \leq 0.01$. * Significant at $P \leq 0.001$.**

centration from a lower depth. This resulted in a slightly more uniform distribution of clay and sand concentration within the surface 30 cm. One of the legacy effects of long-term agricultural cropping in the southern Piedmont is the generally higher clay concentration at the soil surface due to abundant erosion of the surface horizon (Trimble, 1974) and mixing of sandy surface soil with the clayey Bt horizon with plowing. In a nearby secondary forest (at least 130 yr without plowing), clay concentration averaged 0.15 kg kg^{-1} in the surface 20 cm (Franzluebbers et al., 2000c), which was slightly lower than that measured under CT (0.19 kg kg^{-1}).

Initially, soil bulk density was low at the soil surface and increased with depth (Fig. 2). This depth distribution pattern was similar to that reported for long-term pasture in northern Georgia (Franzluebbers et al., 1999). There were no major differences in bulk density before administering treatment variables, except for a significant ($P \leq 0.05$) tillage × cover crop management interaction effect at depths of 3 to 6 and 0 to 20 cm. Initial random variation in bulk density was relatively low, with a coefficient of variation of 2 to 4% among depth intervals.

At the end of 1 yr of management, soil bulk density was reduced with CT compared with NT at all depths below 6 cm,

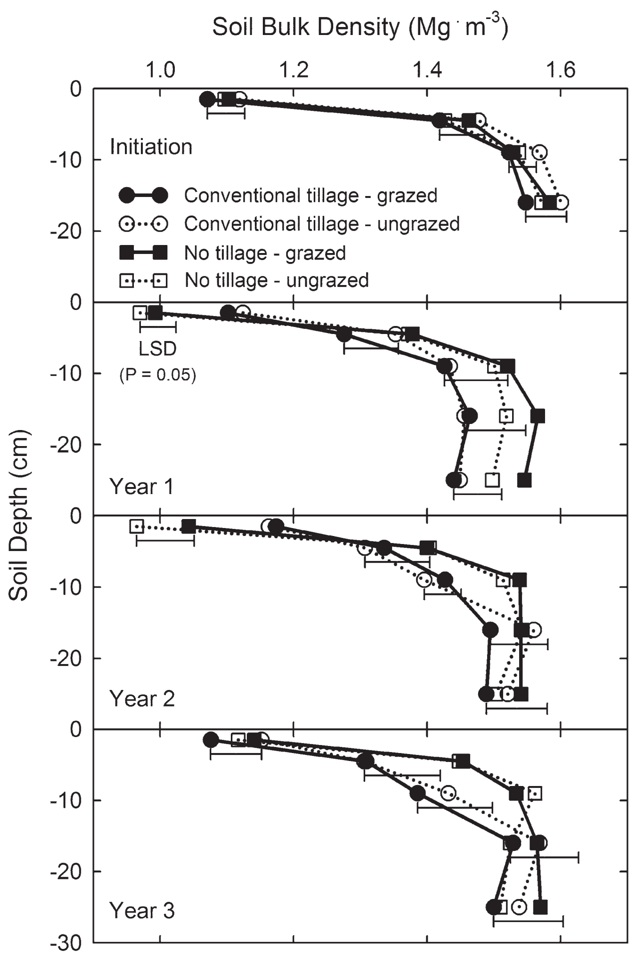

Fig. 2. Depth distribution of soil bulk density as affected by year, tillage, and cover crop management. Error bars denote significance (*P* = 0.05) among tillage and cover crop management variables within a depth and year of sampling. Depth of conventional tillage was initially 25 to 30 cm with a moldboard plow and thereafter 15 to 20 cm with an offset disk.

but was greater with CT than with NT at a depth of 0 to 3 cm (Fig. 2). Therefore, inversion tillage lessened the highly stratified depth distribution of bulk density that occurred following long-term pasture. Treatment effects other than tillage, including whether cover crops were grazed by cattle or not, were not significant at any depth in the first year. At the end of 2 yr, bulk density remained greater with CT than with NT at a depth of 0 to 3 cm but was lower with CT than with NT at depths of 3 to 6 and 6 to 12 cm. No differences due to tillage occurred below 12 cm, indicating that moldboard plowing loosened the soil below 12 cm only during the first year and not significantly thereafter when shallower tillage with offset disks was used. At the end of 3 yr, bulk density became no different between tillage systems at a depth of 0 to 3 cm, and other effects remained the same as at 2 yr, including no difference due to cover crop management. The difference in bulk density between tillage systems was significantly lower summed to a depth of 12 cm under CT (1.31 Mg m^{-3}) than under NT (1.42 Mg m^{-3}) ($P = 0.02$).

Summed to a depth of 30 cm, soil bulk density was significantly lower under CT than under NT only at the end of 1 yr (1.40 vs.1.46 Mg m^{-3} at the end of 1 yr [$P = 0.02$], 1.44 vs. 1.46 Mg m^{-3} at the end of 2 yr [$P = 0.26$], and 1.44 vs. 1.49 Mg m^{-3} at the end of 3 yr [$P = 0.08$]). The effect of moldboard plowing on soil-profile bulk density was short lived in this soil.

Depth Distribution of Soil Carbon and Nitrogen Fractions

Initial distribution of total organic C was highly stratified with depth (Fig. 3) and inversely related to soil bulk density (Fig. 2). There were no major differences in total organic C before administering treatment variables, except for a difference ($P = 0.03$) among assigned treatments at a depth of 3 to 6 cm. The depth distribution of total organic C reflected the predominantly surface input of organic matter from senescent grass and dung deposited by cattle grazing these perennial pastures for 20 yr. Initial depth distribution of total organic C was similar to that reported for other pastures in northern Georgia (Franzluebbers et al., 1999, 2000c).

At the end of 1 yr of management, a dramatic change in total organic C distribution occurred under CT as a result of surface inversion with the moldboard plow. Total organic C was lower under CT than under NT at a depth of 0 to 3 cm (11 vs. 39 g kg^{-1} [$P < 0.001$])] and 3 to 6 cm (11 vs. 20 g kg^{-1} [$P < 0.001$]), but greater under CT than under NT at a depth of 12 to 20 cm (13 vs. 7 g kg^{-1} [$P < 0.001$]) and 20 to 30 cm (9 vs. 5 g kg^{-1} [$P = 0.001$]). No other treatment effects were significant at the end of 1 yr.

At the end of 2 yr, all of the same tillage effects on total organic C remained similar (Fig. 3). In addition, total organic C was lower when cover crops were grazed than not grazed at depths of 0 to 3 cm (24 vs. 26 g kg^{-1} [$P = 0.01$]) and 3 to 6 cm (16 vs. 18 g kg^{-1} [$P = 0.03$]). At the end of 3 yr, the depth distribution of total organic C remained greatly affected by tillage system, but cropping system and cover crop management effects were not significant at any depth.

The depth distribution of particulate organic C and N, microbial biomass C, and potential C and N mineralization in each year generally followed a similar pattern to that observed for total organic C (data not shown). The organic resources controlled by tillage placement had an overriding influence on all soil C and N fractions. The major impact of tillage management on depth distribution of soil C and N fractions is consistent with several long-term studies in Kentucky, Minnesota, Nebraska, and West Virginia (Doran, 1980, 1987), in Michigan and Ohio (Dick et al., 1998), and in Texas (Franzluebbers et al., 1994; Potter et al., 1998).

Depth distribution of soil C and N fractions was little affected whether cover crops were grazed by cattle or not and even less so whether the cover crop was grown in winter or summer. Literature is sparse to support our results on the general lack of change in soil C and N fractions with cattle grazing of cover crops and whether cover crops are grown in summer or winter. Winter cover crops increased soil microbial biomass C and potential C mineralization in a silt loam from Oregon compared with no cover crop (Mendes et al., 1999). With 3 yr of hairy vetch (*Vicia villosa* Roth) cover cropping on a sandy loam in central Georgia, total organic C was not different but total soil N was greater than without cover cropping (Sainju et al., 2000). Potential C and N mineralization and residual inorganic N were also greater with winter cover cropping than without.

The stratification ratio of all soil C and N fractions was lower under CT than under NT (Tables 1–6), averaging 1.1 and 3.8, respectively, for total organic C, 1.1 and 3.9 for total soil N, 1.1 and 8.6 for particulate organic C, 1.9 and 5.6 for soil microbial biomass C, 2.0 and 6.5 for potential C mineralization, 1.2 and 2.7 for potential N mineralization, and 1.4 and 2.7 for residual inorganic N. There was a also a significant interaction of cropping system × tillage × cover crop management for stratification ratio of total soil N, particulate organic C, soil microbial biomass C, and potential N mineralization, in which ratios were greater when the winter cover crop was grazed than not grazed but lower when the summer cover crop was grazed than not grazed. High stratification ratios could be indicative of high soil quality (Franzluebbers, 2002a), although the relationships between stratification ratio and soil functions (e.g., infiltration, nutrient cycling and retention, biological diversity, etc.) need to be quantitatively characterized (e.g., McCarty et al., 1998; Franzluebbers, 2002b).

Management Impacts on Soil Carbon and Nitrogen Fractions across Years

In general, management effects were similar from 1 to 3 yr of crop management following termination of pasture. Because of this similarity, as well as the consistent sampling of the additional 20- to 30-cm depth in these years, an analysis across the 3 yr was conducted to evaluate the consistent influence of management variables on soil C and N fractions. Absolute values of C and N fractions may have changed among years (as shown below) but relative differences among treatments were generally similar.

Total soil N was mostly influenced by tillage system, for which effects were CT < NT within the surface 6 cm, CT = NT at 6 to 12 cm, and CT > NT below 12 cm (Table 1). A significant tillage × cover crop management effect occurred for total soil N at a depth of 0 to 3 cm and for surface residue N due to relatively lower concentration when grazed than when ungrazed under NT, but no difference under CT. Consumption of cover-crop forage by cattle and deposition of N as feces may have created greater opportunities for gaseous loss of N (Singurindy et al., 2006) than cover crop residues left to decompose on the soil surface. Conditions for decomposition of cover crop and animal feces may have been more similar under CT. Cropping system had no effect on total soil N or on surface residue N. Total soil N was lower under CT than under NT summed to a depth of 6 cm (0.70 vs. 1.59 g kg^{-1} [$P < 0.001$]), but was not different when summed to a depth of 30 cm. None of the management variables affected total soil N or total stock of N at a depth of 0 to 30 cm.

Particulate organic C was also mostly affected by tillage system, the effects of which were significant at all depths, except summed to 30 cm (Table 2). The only other significant management effect occurred at a depth of 0 to 3 cm, in which particulate organic C was lower when the summer cover crop was grazed than when it was not grazed (8.4 vs. 10.4 g kg^{-1} [$P = 0.005$]), but it was not affected by grazing of the winter cover crop. The ungrazed summer cover crop appears to have undergone less decomposition and contributed more to the coarse fraction of organic C than the grazed summer cover crop. Why this difference did not occur in the winter cover crop is unclear.

Soil microbial biomass C was greatly affected by tillage system at all depths, except only as a trend effect ($P = 0.09$) when

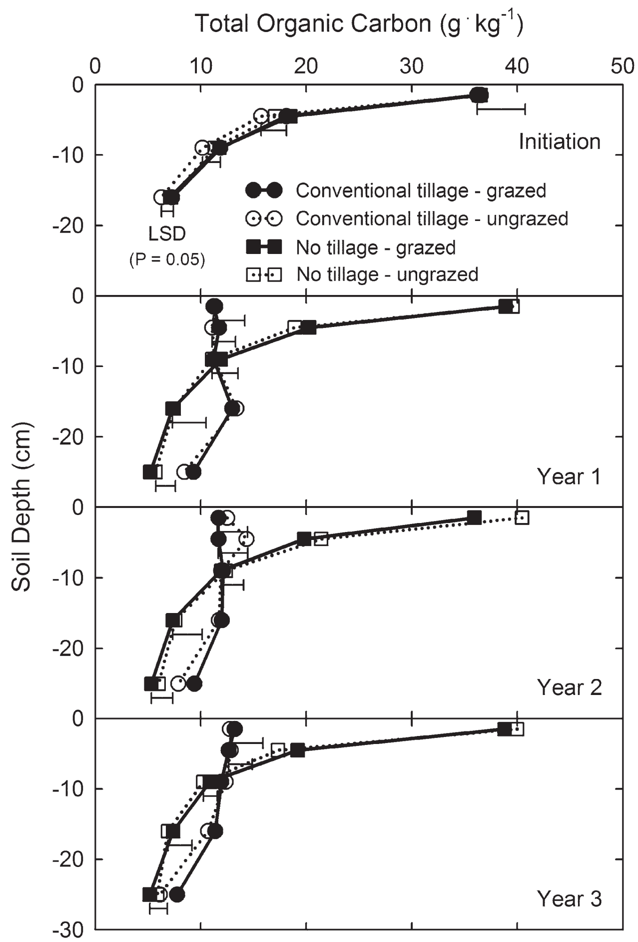

Fig. 3. Depth distribution of total organic C as affected by year, tillage, and cover crop management. Error bars denote significance ($P = 0.05$) among tillage and cover crop management variables within a depth and year of sampling.

Table 1. Total soil N and surface residue N averaged across Years 1, 2, and 3 as affected by cropping system, tillage, and cover crop management. Total soil N was analyzed by individual soil depth increments, as well as summed to depths of 0 to 6 and 0 to 30 cm. Stratification ratio of total soil N was calculated as the weighted concentration at 0 to 6 cm divided by that at 12 to 20 cm.

Cropping system†	Tillage†	Cover crop	Total soil N 0–3 cm	3–6 cm	6–12 cm	12–20 cm	20–30 cm	0–6 cm	0–30 cm	Surface residue N	Total stock (residue + 30 cm)	Stratification ratio
			g kg^{-1}					Mg ha^{-1}				kg kg^{-1}
SGWC	CT	grazed	1.00	0.98	0.94	0.97	0.77	0.69	3.97	0.02	3.99	1.1
		ungrazed	0.98	1.06	0.92	0.95	0.65	0.74	4.00	0.01	4.01	1.2
	NT	grazed	3.05	1.68	0.90	0.53	0.47	1.61	3.88	0.10	3.98	4.3
		ungrazed	3.11	1.71	0.90	0.64	0.51	1.63	4.14	0.12	4.26	3.7
WGSC	CT	grazed	0.98	0.89	0.87	0.94	0.69	0.67	3.90	0.02	3.92	1.1
		ungrazed	0.99	0.98	0.94	1.00	0.67	0.71	4.19	0.01	4.20	1.0
	NT	grazed	2.80	1.51	0.88	0.60	0.50	1.54	3.96	0.10	4.06	3.6
		ungrazed	3.12	1.47	0.91	0.54	0.54	1.57	3.82	0.13	3.95	4.1
LSD (P = 0.05)			0.24	0.18	0.11	0.15	0.13	0.11	0.42	0.03	0.42	0.4
Source of variation		df						P value				
Crop		1, 9	0.71	0.23	0.73	0.95	0.93	0.47	0.86	0.43	0.88	0.41
Tillage		1, 9	<0.001	<0.001	0.70	<0.001	<0.001	<0.001	0.69	<0.001	0.84	<0.001
Crop × tillage		1, 9	0.76	0.61	0.86	0.75	0.38	0.73	0.60	0.89	0.60	0.67
Cover crop (CC)		1, 12	0.04	0.35	0.69	0.74	0.61	0.33	0.55	0.16	0.53	0.84
Crop × CC		1, 12	0.08	0.76	0.46	0.68	0.39	0.96	0.84	0.81	0.85	0.06
Tillage × CC		1, 12	0.03	0.32	0.93	0.97	0.08	0.73	0.77	0.007	0.84	0.72
Crop × tillage × CC		1, 12	0.15	0.66	0.64	0.29	0.46	0.81	0.37	0.44	0.38	0.02
Year		2, 48	<0.001	0.007	<0.001	0.90	0.20	<0.001	0.006	<0.001	0.004	0.001
Year × crop × tillage × CC		14, 48	0.001	0.13	0.11	0.33	0.21	<0.001	0.21	<0.001	0.20	0.05

† SGWC, summer grain with winter cover crop; WGSC, winter grain with summer cover crop; CT, conventional tillage; NT no-till.

summed to a depth of 30 cm (Table 3). Similar to total organic C, surface soil was depleted in microbial biomass C under CT compared with NT. Soil microbial biomass C below 6 cm was enriched under CT compared with NT. When summed to a depth of 30 cm, microbial biomass C was lower under CT than under NT in the summer grain with winter cover crop system (1623 vs. 1756 mg kg^{-1} [P = 0.005]), but not different between tillage systems in the winter grain with summer cover crop system. Also at this depth, soil microbial biomass C was greater under the summer grain with winter cover crop than under the winter grain with summer cover crop (1690 vs. 1624 mg kg^{-1} [P = 0.03]). Two cover crop management effects occurred. At a depth of 0 to 3 cm, soil microbial biomass C was lower when the summer cover crop was grazed than when it was not grazed (1019 vs. 1176 mg kg^{-1} [P = 0.009]), but a reverse trend occurred under the winter cover crop (1259 vs. 1162 mg kg^{-1} [P = 0.10]). At a depth of 3 to 6 cm, soil microbial biomass C was greater when cover crops were grazed than not grazed under NT (753 vs. 670 mg kg^{-1} [P = 0.02]) but not different under CT. Enhanced soil microbial biomass C with the addition of animal manure has been reported before (Fraser et al., 1988; Carpenter-Boggs et al., 2000), but our study compared

Table 2. Particulate organic C averaged across Years 1, 2, and 3 as affected by cropping system, tillage, and cover crop management. Particulate organic C was analyzed by individual soil depth increments, as well as summed to depths of 0 to 6 and 0 to 30 cm. Stratification ratio of particulate organic C was calculated as the weighted concentration at 0 to 6 cm divided by that at 12 to 20 cm.

Cropping system†	Tillage†	Cover crop	Particulate organic C 0–3 cm	3–6 cm	6–12 cm	12–20 cm	20–30 cm	0–6 cm	0–30 cm	Stratification ratio
			g kg^{-1}					Mg ha^{-1}		kg kg^{-1}
SGWC	CT	grazed	3.0	3.2	3.4	3.6	2.3	2.2	12.3	1.0
		ungrazed	2.9	3.3	3.3	3.2	1.9	2.2	11.5	1.2
	NT	grazed	17.8	6.2	2.8	1.4	0.8	7.8	13.3	8.3
		ungrazed	17.2	6.1	3.1	1.7	1.0	7.5	13.8	7.8
WGSC	CT	grazed	2.9	3.1	3.6	3.9	2.0	2.2	12.7	1.1
		ungrazed	3.4	3.4	4.0	4.2	1.6	2.4	13.2	1.0
	NT	grazed	13.8	5.9	3.0	1.4	0.7	6.9	12.4	6.9
		ungrazed	17.5	5.3	2.6	1.1	0.7	7.5	12.2	11.4
LSD (P = 0.05)			2.2	3.1	0.7	1.2	0.8	0.9	2.2	1.9
Source of variation		df					P value			
Crop		1, 9	0.54	0.66	0.65	0.60	0.39	0.73	0.86	0.53
Tillage		1, 9	<0.001	<0.001	0.03	<0.001	0.003	<0.001	0.45	<0.001
Crop × tillage		1, 9	0.46	0.66	0.30	0.12	0.89	0.54	0.12	0.51
Cover crop (CC)		1, 12	0.09	0.77	0.82	0.93	0.37	0.36	0.99	0.15
Crop × CC		1, 12	0.02	0.78	0.82	0.98	0.68	0.13	0.74	0.12
Tillage × CC		1, 12	0.17	0.38	0.59	0.92	0.15	0.99	0.73	0.18
Crop × tillage × CC		1, 12	0.07	0.61	0.29	0.21	0.74	0.35	0.30	0.08
Year		2, 48	0.02	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Year × crop × tillage × CC		14, 48	0.31	0.20	0.95	0.41	0.009	0.14	0.24	<0.001

† SGWC, summer grain with winter cover crop; WGSC, winter grain with summer cover crop; CT, conventional tillage; NT no-till.

Table 3. Soil microbial biomass C averaged across Years 1, 2, and 3 as affected by cropping system, tillage, and cover crop management. Soil microbial biomass C was analyzed by individual soil depth increments, as well as summed to depths of 0 to 6 and 0 to 30 cm. Stratification ratio of soil microbial biomass C was calculated as the weighted concentration at 0 to 6 cm divided by that at 12 to 20 cm.

Cropping system†	Tillage†	Cover crop	Soil microbial biomass C							Stratification ratio
			0–3 cm	3–6 cm	6–12 cm	12–20 cm	20–30 cm	0–6 cm	0–30 cm	
			mg kg^{-1}					kg ha^{-1}		kg kg^{-1}
SGWC	CT	grazed	733	618	440	337	261	469	1586	2.3
		ungrazed	697	579	420	393	272	459	1661	1.8
	NT	grazed	1785	769	372	229	217	852	1798	5.9
		ungrazed	1628	721	355	259	212	773	1714	4.6
WGSC	CT	grazed	588	553	389	409	255	415	1593	1.5
		ungrazed	686	607	461	359	272	468	1690	1.9
	NT	grazed	1450	737	322	239	191	778	1646	5.3
		ungrazed	1665	618	281	202	208	766	1566	6.5
LSD (P = 0.05)			216	116	81	85	69	79	249	2.1
Source of variation		df					P value			
Crop		1, 9	0.21	0.22	0.22	0.87	0.64	0.07	0.03	0.76
Tillage		1, 9	<0.001	0.005	0.005	<0.001	0.009	<0.001	0.09	<0.001
Crop × tillage		1, 9	0.68	0.48	0.30	0.16	0.75	0.58	0.01	0.22
Cover crop (CC)		1, 12	0.52	0.09	0.95	0.98	0.42	0.47	0.96	0.87
Crop × CC		1, 12	0.02	0.79	0.37	0.09	0.55	0.06	0.88	0.01
Till × CC		1, 12	0.98	0.04	0.16	0.89	0.75	0.06	0.07	0.88
Crop × tillage × CC		1, 12	0.21	0.07	0.14	0.70	0.76	0.96	0.92	0.16
Year		2, 48	0.13	0.14	0.001	0.36	<0.001	0.34	<0.001	0.38
Year × crop × tillage × CC		14, 48	0.002	0.02	0.44	0.69	0.01	0.001	0.18	0.89

† SGWC, summer grain with winter cover crop; WGSC, winter grain with summer cover crop; CT, conventional tillage; NT no-till.

processing of the same in situ cover crop through grazing animals or leaving it to decompose without animal consumption.

Potential C mineralization was largely affected by tillage management, with effects significant at all depths except at 3- to 6- and 0- to 30-cm depths (Table 4). All other soil properties were negatively affected by CT compared with NT at a depth of 3 to 6 cm, but potential C mineralization was not. Cover crop management interactions occurred with tillage and cropping system within the surface three depths. At a depth of 0 to 3 cm, potential C mineralization was 2.7 times greater with NT than with CT when cover crops were grazed and 2.2 times greater with NT than with CT when not grazed. At this same depth, potential C mineralization tended to be greater when the winter cover crop was grazed than not grazed, but tended to be lower when the summer cover crop was grazed than not grazed. At depths of 3 to 6 and 6 to 12 cm, potential C mineralization was lower when the summer cover crop was grazed than not grazed under CT but not under NT and not

Table 4. Potential C mineralization averaged across Years 1, 2, and 3 as affected by cropping system, tillage, and cover crop management. Potential C mineralization was analyzed by individual soil depth increments, as well as summed to depths of 0 to 6 and 0 to 30 cm. Stratification ratio of potential C mineralization was calculated as the weighted concentration at 0 to 6 cm divided by that at 12 to 20 cm.

Cropping system†	Tillage†	Cover crop	Potential C mineralization							Stratification ratio
			0–3 cm	3–6 cm	6–12 cm	12–20 cm	20–30 cm	0–6 cm	0–30 cm	
			mg kg^{-1} $(24\ d)^{-1}$					kg ha^{-1} $(24\ d)^{-1}$		kg kg^{-1}
SGWC	CT	grazed	670	565	415	299	198	427	1394	2.1
		ungrazed	618	559	411	280	180	425	1353	2.2
	NT	grazed	1662	621	271	161	124	758	1389	7.0
		ungrazed	1524	674	312	176	130	722	1403	6.6
WGSC	CT	grazed	467	466	369	314	177	339	1276	1.6
		ungrazed	684	593	491	306	160	463	1480	2.2
	NT	grazed	1396	569	271	152	112	689	1286	6.4
		ungrazed	1376	527	272	148	118	640	1237	6.1
LSD (P = 0.05)			184	92	70	49	32	72	142	1.0
Source of variation		df					P value			
Crop		1, 9	0.14	0.14	0.92	0.94	0.07	0.08	0.16	0.22
Tillage		1, 9	<0.001	0.23	<0.001	<0.001	<0.001	<0.001	0.30	<0.001
Crop × tillage		1, 9	0.44	0.42	0.41	0.17	0.61	0.34	0.14	0.74
Cover crop (CC)		1, 12	0.95	0.08	0.02	0.81	0.41	0.50	0.29	0.98
Crop × CC		1, 12	0.006	0.59	0.16	0.89	0.99	0.05	0.14	0.70
Tillage × CC		1, 12	0.02	0.14	0.21	0.58	0.11	0.002	0.12	0.36
Crop × tillage × CC		1, 12	0.22	0.006	0.01	0.66	0.94	0.02	0.02	0.83
Year		2, 48	0.02	0.007	0.002	0.11	0.11	0.02	<0.001	0.05
Year × crop × tillage × CC		14, 48	0.03	0.12	0.35	0.03	<0.001	0.01	0.01	<0.001

† SGWC, summer grain with winter cover crop; WGSC, winter grain with summer cover crop; CT, conventional tillage; NT no-till.

Table 5. Potential N mineralization averaged across Years 1, 2, and 3 as affected by cropping system, tillage, and cover crop management. Potential N mineralization was analyzed by individual soil depth increments, as well as summed to depths of 0 to 6 and 0 to 30 cm. Stratification ratio of potential N mineralization was calculated as the weighted concentration at 0 to 6 cm divided by that at 12 to 20 cm.

Cropping system†	Tillage†	Cover crop	Potential N mineralization							Stratification ratio
			0–3 cm	3–6 cm	6–12 cm	12–20 cm	20–30 cm	0–6 cm	0–30 cm	
			mg kg^{-1} (24 d)$^{-1}$					kg ha^{-1} (24 d)$^{-1}$		kg kg^{-1}
SGWC	CT	grazed	42	31	30	33	23	25	121	1.1
		ungrazed	31	29	32	29	18	22	108	1.3
	NT	grazed	121	52	28	12	11	57	113	8.2
		ungrazed	121	67	31	20	13	63	132	5.0
WGSC	CT	grazed	30	34	32	29	21	23	115	1.2
		ungrazed	32	36	38	37	21	25	131	1.1
	NT	grazed	115	44	26	14	10	56	111	6.4
		ungrazed	131	49	24	13	11	60	113	7.3
LSD (P = 0.05)			21	13	10	9	4	8	17	1.9
Source of variation		df					P value			
Crop		1, 9	0.80	0.38	0.87	0.94	0.63	0.72	0.85	0.85
Tillage		1, 9	<0.001	0.001	0.03	<0.001	<0.001	<0.001	0.75	<0.001
Crop × tillage		1, 9	0.58	0.06	0.10	0.40	0.43	0.18	0.10	0.82
Cover crop (CC)		1, 12	0.78	0.03	0.40	0.32	0.32	0.99	0.20	0.28
Crop × CC		1, 12	0.20	0.54	0.89	0.70	0.32	0.29	0.54	0.07
Tillage × CC		1, 12	0.26	0.03	0.47	0.77	0.03	0.47	0.37	0.27
Crop × tillage × CC		1, 12	0.91	0.09	0.49	0.08	0.09	0.85	0.03	0.05
Year		2, 48	0.001	0.001	0.03	0.02	0.09	<0.001	<0.001	0.02
Year × crop × tillage × CC		14, 48	0.05	0.003	0.65	0.90	0.77	0.006	0.61	0.43

† SGWC, summer grain with winter cover crop; WGSC, winter grain with summer cover crop; CT, conventional tillage; NT no-till.

under any tillage system with the winter cover crop. This same effect occurred when summed to depths of 6 and 30 cm. Root proliferation and subsequent rhizodeposition may have been inhibited by grazing of the summer crop (Mousel et al., 2005), resulting in lower potential C mineralization. Why this occurred primarily under CT and not under NT is not easily explained.

Potential N mineralization was affected by tillage system at all depths (Table 5). Tillage effects were CT < NT at depths of 0 to 3 and 3 to 6 cm and CT > NT at depths of 6 to 12, 12 to 20, and 20 to 30 cm. Cropping system had no overall effect on potential N mineralization. Cover crop management interacted with tillage system at some depths. At a depth of 3 to 6 cm, potential N mineralization was lower when cover crops were grazed than not grazed under NT (48 vs. 58 mg kg^{-1} [P = 0.008]) but not different under CT. At a depth of 20 to 30 cm, potential N mineralization tended to be greater when cover crops were grazed than not grazed under CT (due to the effect under summer grain with winter cover crop) but not different under NT. Summed to a depth of 30 cm, the overall tillage effect on potential N mineralization was not significant, but significant interactions occurred. Potential N mineralization was CT < NT when the winter cover crop was not grazed, but CT > NT when the summer cover crop was not grazed. This result suggests differences in quality of plant material and animal feces supplied to soil under the two cropping systems.

Apparent nitrification of NH_4 to NO_3 (i.e., the fraction of net N mineralized as NO_3–N) during the 24-d incubation became different between tillage systems with increasing depth in the soil profile. Apparent nitrification averaged 100% at a depth of 0 to 3 cm and 80% at a depth of 3 to 6 cm, with no differences due to tillage or other management effect. At a depth of 6 to 12 cm, apparent nitrification was greater with CT than with NT and this effect became stronger with increasing depth. Apparent nitrification averaged 77% under CT and 61% under NT at a depth of 6 to 12 cm (P = 0.01), averaged 84% under CT and 50% under NT at a depth of 12 to 20 cm (P < 0.001), and averaged 73% under CT and 25% under NT at a depth of 20 to 30 cm (P < 0.001). It appears that nitrifying bacteria were either present at very low numbers following long-term pasture or their activity was suppressed. Lower O_2 conditions deep in the profile might be thought to inhibit nitrifying bacteria, but any limitation on O_2 would have been alleviated during the aerobic incubation in the laboratory. Soil NO_3 under undisturbed perennial ecosystems has often been found in low concentration, giving rise to the suggestion that plant-produced metabolites could be inhibiting the activity of nitrifying bacteria (Rice and Pancholy, 1973, 1974). Plant-produced secondary metabolites have been shown to inhibit nitrification in soil. Examples include tannins from *Pinus*, *Vaccinium*, *Arctostaphylos*, *Rhododendron*, and *Gaultheria* (Kraus et al., 2004), isothyocyanates from crucifers such as mustard (Bending and Lincoln, 2000), and triterpen saponins, polysaccharides, or flavenoids from *Astragalus* (Mao et al., 2006). Other results suggest that enhanced immobilization of N by abundantly available C from root exudates may be a leading cause for low NO_3 in soil (Odu and Akerele, 1973; Kraus et al., 2004).

Residual inorganic N (i.e., before incubation), like many of the organic C and N fractions, was largely affected by tillage system (Table 6). The long-term effects of management on organic C and N fractions resulted in subsequent changes in inorganic N, in the form of both NH_4–N and NO_3–N. Tillage effects were CT < NT at depths of 0 to 3 cm for both NH_4–N and NO_3–N and 3 to 6 cm for NO_3–N only. Tillage

Table 6. Residual inorganic N (NH_4–N, NO_3–N, and their sum) averaged across Years 1, 2, and 3 as affected by cropping system, tillage, and cover crop management. Inorganic N was analyzed by individual soil depth increments, as well as summed to depths of 0 to 6 and 0 to 30 cm. Stratification ratio of residual inorganic N was calculated as the weighted concentration at 0 to 6 cm divided by that at 12 to 20 cm.

Cropping system†	Tillage†	Cover crop	Residual inorganic N												Stratification ratio
			NH_4–N					NO_3–N					Inorganic sum		
			0–3 cm	3–6 cm	6–12 cm	12–20 cm	20–30 cm	0–3 cm	3–6 cm	6–12 cm	12–20 cm	20–30 cm	0–6 cm	0–30 cm	
			mg kg^{-1}										kg ha^{-1}		kg kg^{-1}
SGWC	CT	grazed	10.5	7.6	6.2	6.0	4.7	3.3	3.3	4.5	4.3	4.8	9	43	1.3
		ungrazed	11.0	7.8	6.3	5.7	4.5	2.9	3.4	5.3	3.7	3.6	9	41	1.4
	NT	grazed	16.1	9.0	5.2	4.7	4.0	10.7	7.3	3.0	3.0	2.6	15	42	2.8
		ungrazed	14.2	9.0	5.5	4.4	3.9	9.7	5.1	2.8	2.6	2.6	13	39	2.7
WGSC	CT	grazed	10.0	7.5	6.2	5.5	4.4	4.0	4.3	4.6	4.8	4.4	9	44	1.3
		ungrazed	14.2	7.2	6.9	5.9	4.7	4.1	3.3	3.6	4.1	3.5	10	43	1.5
	NT	grazed	14.7	8.9	5.5	4.5	3.8	10.6	6.1	3.4	2.5	2.6	15	41	2.9
		ungrazed	14.7	7.2	5.8	4.8	3.9	13.1	5.9	3.5	3.4	3.1	14	42	2.6
LSD (P = 0.05)			5.0	1.6	1.3	0.9	0.8	2.5	1.8	1.6	1.2	1.3	3	7	0.5
Source of variation		df							P value						
Crop		1, 9	0.63	0.21	0.53	0.90	0.34	0.14	0.84	0.85	0.33	0.99	0.17	0.29	0.99
Tillage		1, 9	0.003	0.06	0.10	<0.001	<0.001	<0.001	0.001	0.04	0.001	<0.001	<0.001	0.26	<0.001
Crop × tillage		1, 9	0.33	0.47	0.95	0.48	0.57	0.68	0.57	0.35	0.57	0.48	0.47	0.92	0.82
Cover crop (CC)		1, 12	0.48	0.22	0.23	0.94	0.96	0.49	0.05	0.38	0.43	0.15	0.63	0.47	0.67
Crop × CC		1, 12	0.16	0.12	0.60	0.25	0.33	0.05	0.55	0.50	0.29	0.48	0.45	0.22	0.91
Tillage × CC		1, 12	0.11	0.25	0.85	0.85	0.89	0.31	0.33	0.43	0.15	0.02	0.12	0.94	0.08
Crop × tillage × CC		1, 12	0.62	0.42	0.58	0.82	0.66	0.12	0.08	0.22	0.20	0.81	0.71	0.53	0.62
Year		2, 48	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.03	<0.001	<0.001	<0.001	0.001	<0.001
Year × crop × tillage × CC		14, 48	<0.001	0.13	0.17	0.04	<0.001	<0.001	<0.001	0.09	0.12	0.007	<0.001	0.004	0.006

† SGWC, summer grain with winter cover crop; WGSC, winter grain with summer cover crop; CT, conventional tillage; NT no-till.

effects were CT > NT for only NO_3–N at a depth of 6 to 12 cm and for both NH_4–N and NO_3–N at depths of 12 to 20 and 20 to 30 cm. Cropping system and cover crop management did not affect NH_4–N at any depth. Cover crop management did affect NO_3–N at some depths, but differences were <3 mg kg^{-1}. Summed to 30 cm, there were no differences in residual inorganic N among management systems.

The flush of CO_2 following rewetting of dried soil was highly related to other soil C and N fractions (Fig. 4). As an indicator, the flush of CO_2 appeared to most closely represent the soil microbial biomass C and potential C mineralization fractions. These relationships were generally consistent with previous relationships in Alberta, British Columbia, Georgia, Maine, and Texas (Franzluebbers et al., 2000a) and in North Carolina (Franzluebbers and Brock, 2007).

Water-Stable Aggregate Distribution of Soil Carbon and Nitrogen Fractions

Separation of soil into water-stable aggregate fractions revealed similar tillage effects on total organic C throughout the surface soil profile as with whole-soil analysis, but also revealed a more exact location of where total organic C was residing (Fig. 5). At a depth of 0 to 3 cm, the total organic C concentration was lower with CT than with NT in all three aggregate fractions analyzed, i.e., large macroaggregates (1–4.75 mm), small macroaggregates (0.25–1 mm), and microaggregates (0.05–0.25 mm). At a depth of 3 to 6 cm, the effect of tillage on total organic C concentration was CT < NT only in the macroaggregate classes at the end of 1 yr of management, but became CT < NT in all aggregate classes at the end of 2 and 3 yr. At a depth of 6 to 12 cm, few differences in total organic C concentration occurred due to tillage, similar to that observed for whole-soil analysis; however, there was an indication that total organic C became dispersed from macroaggregates and appeared in greater concentration in the microaggregate class. At depths of 12 to 20 and 20 to 30 cm, greater concentration of total organic C occurred with CT than with NT, especially in the smaller aggregate classes. The shift from lower C concentration with CT than with NT in macroaggregates near the soil surface to greater concentration with CT than with NT in microaggregates at lower depths in this study was consistent with data from Nebraska (Cambardella and Elliott, 1993) and Alberta and British Columbia (Franzluebbers and Arshad, 1996). Our results are also consistent with data from an old field in Michigan, where aggregate-associated C declined at a depth of 0 to 7 cm during the first 3 yr of tillage compared with undisturbed soil and increased with tillage at a depth of 7 to 20 cm (Grandy and Robertson, 2006).

When averaged across Years 1 to 3, the C concentration of water-stable aggregates was not affected by cropping system at any depth, but was affected by cover crop management in the surface 12 cm. Carbon concentration of small macroaggregates was similar when cover crops were grazed and not grazed under CT at a depth of 0 to 3 cm (4.4 vs. 3.5 g kg^{-1} [P = 0.17]), but was lower when cover crops were grazed than not grazed under NT (10.7 vs. 12.6 g kg^{-1} [P = 0.009]). Carbon concentration of microaggregates was greater when cover crops were grazed than not grazed at depths of 3 to 6 cm (4.1 vs. 3.3 g kg^{-1} [P < 0.001]) and 6 to 12 cm (2.5 vs. 2.3 g kg^{-1} [P = 0.05]). These results suggest some deterioration of aggregate C distribution with cattle grazing than without and longer term research is needed to better define this effect. Plante and McGill (2002) suggested that C storage in macroaggregates could be enhanced in the short term with soil disturbance, but that long-term effects of inversion tillage would probably lead to deterioration of aggregate protection mechanisms for soil organic C.

Carbon concentration of aggregates was greater in macroaggregate classes than in microaggregates at depths of 0 to 3 and 3 to 6 cm under NT (Fig. 5). Under CT, a more uniform distribution of total organic C among aggregate classes occurred. Similar difference in organic C distribution between macroaggregates and microaggregates in response to long-term tillage systems was observed in Nebraska (Cambardella and Elliott, 1993) and in Georgia (Beare et al., 1994). The importance of roots and mycorrhizal fungi to water-stable aggregation has been recognized (Jastrow et al., 1998), but how root and mycorrhizal dynamics interact with grazing of cover crops needs more investigation.

Temporal Dynamics of Soil Carbon and Nitrogen Fractions

Compared with soil under long-term pasture, the contents of all soil C and N fractions did not change with time when cropland was managed under NT (Fig. 6). This suggests that the accumulation of soil C and N fractions under long-term pasture were effectively preserved when annual crops were introduced and managed with NT. Historically, rotation of pastures and crops has relied on moldboard plowing of pasture to kill the perennial vegetation, but also to help mineralize nutrients that are bound within the accumulated organic matter. Results from this study suggest that soil C and N frac-

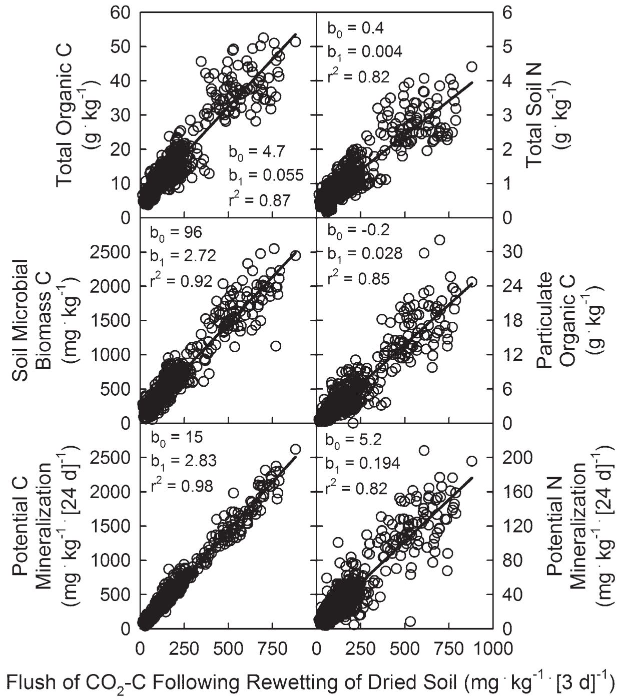

Fig. 4. Relationship of the flush of CO_2 following rewetting of dried soil to total soil organic C, total soil N, soil microbial biomass C, particulate organic C, and potential C and N mineralization; b_0 = intercept, b_1 = slope, and r^2 = strength of relationship. Total number of observations is 646 for each variable.

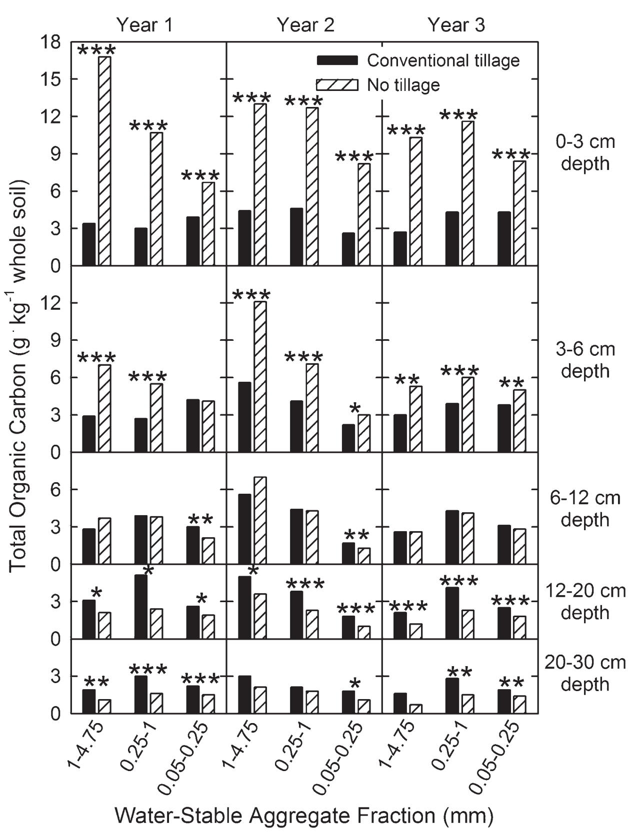

Fig. 5. Total organic C in water-stable aggregate fractions on a whole-soil basis as affected by year of sampling, soil depth, and tillage management. Large macroaggregates are 1 to 4.75 mm, small macroaggregates are 0.25 to 1 mm, and microaggregates are 0.05 to 0.25 mm. * Significant at $P \leq 0.05$. ** Significant at $P \leq 0.01$. * Significant at $P \leq 0.001$.**

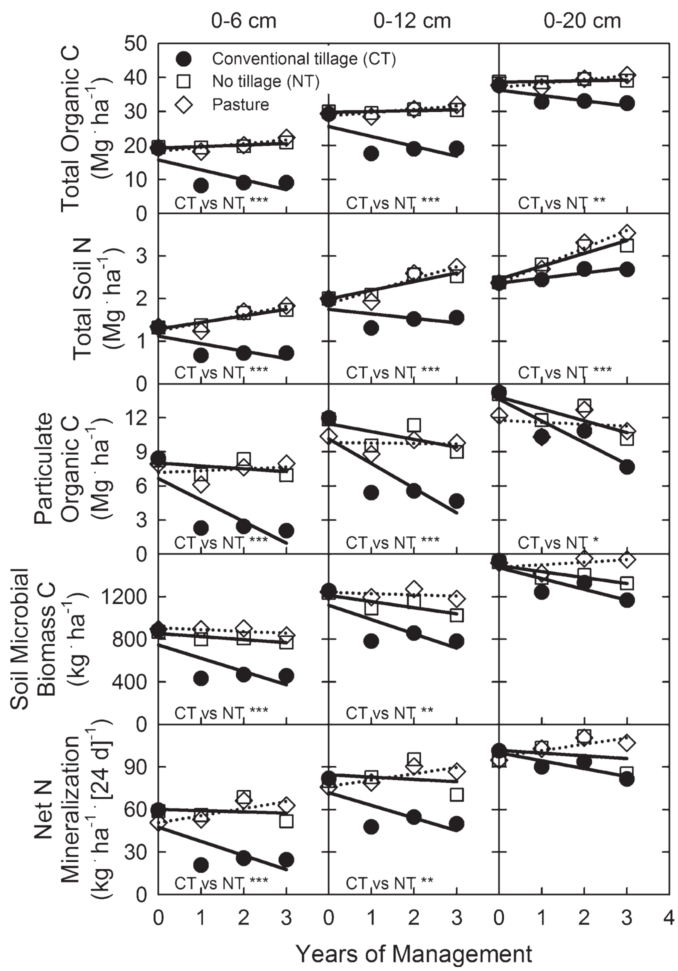

Fig. 6. Temporal change in total soil organic C, total soil N, particulate organic C, soil microbial biomass C, and net N mineralization as affected by management system (conventional-tillage [CT], no-till [NT], and continuation of pasture) and soil depth (0–6, 0–12, and 0–20 cm). Differences in slopes are noted in each panel. * Significant at $P \leq 0.05$. ** Significant at $P \leq 0.01$. * Significant at $P \leq 0.001$. There were no significant differences between pasture and NT.**

tions can be preserved with NT and soil fertility maintained at an adequate level without negatively affecting subsequent crop growth, as crop yields were CT ≤ NT (Franzluebbers and Stuedemann, 2007). It should also be noted that crop residue production in this study was high because of the two crops grown continuously throughout the year. Large differences in crop growth occurred each year, but on average we estimated that 12 to 14 Mg ha^{-1} yr^{-1} of aboveground crop residue was produced, sufficient to prevent large declines in soil organic matter.

Total organic C declined with time under CT and remained stable with time under NT at 0- to 6-, 0- to 12-, and 0- to 20-cm depths (Fig. 6). The inversion of surface soil organic C with moldboard plowing immediately after the initial soil samples were collected resulted in 42% of the total organic C under CT compared with NT in the first year at a depth of 0 to 6 cm. At depths of 0 to 12 and 0 to 20 cm, this proportion was 60 and 85%, respectively. Therefore, the reference depth for calculating the change in stock of total organic C is important, since significant accumulation of stable (at least within 3 yr from initial moldboard plowing) organic C can occur at lower depths of a tillage operation (Fig. 3). The difference in slope between CT and NT was 3.37 Mg C ha^{-1} yr^{-1} at a depth of 0 to 6 cm, 3.15 Mg C ha^{-1} yr^{-1} at a depth of 0 to 12 cm, 1.73 Mg C ha^{-1} yr^{-1} at a depth of 0 to 20 cm, and 1.17 Mg C ha^{-1} yr^{-1} at a depth of 0 to 30 cm (0–30-cm rate calculated assuming values of 4.5 g kg^{-1} of organic C and bulk density of 1.43 Mg m^{-3}; derived from trends in properties under pasture sampled in Years 1–3) (Fig. 6). Differences in slopes of total organic C between CT and NT were highly significant at a shallow surface depth and became less significant with increasing depth, with the difference at 0 to 30 cm not significant (P = 0.11). Statistically, the difference in total organic C between CT and NT may not have been significant, but in practicality, the difference of 1.2 Mg C ha^{-1} yr^{-1} at a depth of 0 to 30 cm is at the high range of reported soil organic C sequestration estimates for NT in the southeastern United States (Franzluebbers, 2005). In Michigan on Typic Hapludalfs, total organic C was not different between an undisturbed old field and adjacent plots tilled annually during the first 3 yr when summed to a depth of 0 to 20 cm (Grandy and Robertson, 2006). The warmer environment in our experiment should have promoted greater oxidation of incorporated organic matter.

Within individual years at a depth of 0 to 30 cm, total organic C was not statistically different between CT and NT at the end of 1 yr (45.4 vs. 46.7 Mg ha^{-1} [P = 0.45]) and at the end of 2 yr (45.8 vs. 47.9 Mg ha^{-1} [P = 0.35]), but was significant at the end of 3 yr (42.6 vs. 47.4 Mg ha^{-1} [P < 0.001]). At the end of 3 yr, the total content of potential C mineralization to a depth of 0 to 30 cm was also lower under CT than under NT (1240 vs. 1371 kg ha^{-1} 24 d^{-1} [P = 0.02]). The flush of CO_2 following rewetting of dried soil was lower under CT than under NT, but only in the summer grain with winter cover crop system (425 vs. 494 kg ha^{-1} 3 d^{-1} [P < 0.001]). Total contents of other soil C and N fractions at the end of 3 yr were not different between tillage systems, but probabilities indicated some trends that will require more time for evaluation (particulate organic C (9.4 [CT] vs. 11.0 [NT] Mg ha^{-1} [P = 0.12]), soil microbial biomass C (1475 [CT] vs. 1612 [NT] kg ha^{-1} [P = 0.14]), and potential N mineralization (111 [CT] vs. 102 [NT] kg ha^{-1} [24 d]$^{-1}$ [P = 0.11]). During the first 3 yr of tillage comparison in Maryland on an Aquic Hapludult, total organic C and soil microbial biomass C also became highly stratified with depth under NT compared with plow tillage, but the total contents within the surface 20 cm did not change significantly (McCarty et al., 1998).

Total soil N increased with time in all management systems when evaluated at a depth of 0 to 20 cm (Fig. 6). The difference in the rate of accumulation of total soil N between CT and NT was 179 kg N ha^{-1} yr^{-1} (P < 0.001), suggesting that N was being redistributed from deeper in the profile to nearer the surface, since yearly application of fertilizer N averaged only 96 kg N ha^{-1} yr^{-1}. Particulate organic C declined with time under both CT and NT at a depth of 0 to 20 cm, but did not change significantly under pasture. The difference in particulate organic C between CT and NT was 0.86 Mg C ha^{-1} yr^{-1} (P = 0.02), suggesting that 50% of the increase in total organic C occurred in the particulate organic fraction. Soil microbial biomass C also declined with time under both CT and NT at a depth of 0 to 20 cm. The difference in soil microbial biomass C between CT and NT was 47 kg C ha^{-1} yr^{-1} (P = 0.11). Potential N mineralization declined with time under CT at all depths, but the difference between CT and NT was not significant at a depth of 0 to 20 cm.

Although recent literature addressing soil C and N fractions has often suggested that more biologically active fractions may be more sensitive to early changes in soil organic matter in response to management differences (Powlson et al., 1987), our results did not support this view. Total organic C and total soil N were equally responsive to the change in management as were particulate, aggregate-associated, microbial biomass, and mineralizable C and N fractions. Statistical differences in various soil C and N fractions among management systems were more difficult to attain, however, with increasing soil depth, as discussed by Baker et al. (2007). Even when we sampled to the depth of tillage operation, however, a statistically and practically significant difference in total organic C could be detected between CT and NT (1.17 Mg C ha^{-1} yr^{-1} by linear regression and 1.60 Mg C ha^{-1} yr^{-1} by difference at the end of 3 yr). Certainly longer term evaluations are warranted to strengthen the conclusions from this relatively short-term evaluation of soil C and N changes due to cropping system, tillage, and cover crop management.

CONCLUSIONS

Tillage system was the dominant source of change in soil C and N fractions in this Typic Kanhapludult, in which long-term perennial pasture was converted to annual cropping systems. Highly stratified depth distribution of soil C and N fractions with pasture was maintained with NT, but was converted to a more uniform depth distribution following moldboard plowing and subsequent disk tillage. There was no indication of reduced stratification of soil C and N fractions with time under NT, although a longer term evaluation is needed. Biologically active fractions of soil C and N responded to management changes similarly to total C and N, which contradicted our hypothesis that they might be more sensitive to early changes in management. Preservation of total organic C with NT did occur preferentially in macroaggregates than in microaggregates. Total contents of most C and N fractions in the upper 30 cm of soil were reduced with CT relative to NT and no differences occurred between NT and the continuation of pasture. The impact of cover crop management was generally limited to the surface 6 cm of soil, in which both negative impacts of grazing (potential C mineralization under CT, total soil N and potential N mineralization under NT, and particulate organic C and soil microbial biomass C with a summer cover crop) and positive impacts of grazing (total organic C in microaggregates, total organic C in small macroaggregates under CT, and soil microbial biomass C and potential C mineralization under NT) occurred. Soil C and N fractions were not adversely affected by grazing of the winter cover crop, contrary to our hypothesis. To preserve high surface-soil C and N fractions and total plow-layer contents, NT cropping following termination of pasture is recommended. Allowing cattle to graze winter or summer cover crops did not consistently negatively influence soil C and N fractions, and therefore, grazing of cover crops can be recommended as a viable conservation approach while intensifying agricultural land use, especially when practiced in combination with NT.

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